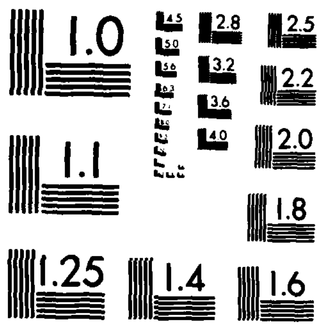
AD-A149 445 OPERATIONAL LOADS MEASUREMENT: A PHILOSOPHY AND ITS IMPLEMENTATION(U) ROYAL AIRCRAFT ESTABLISHMENT FARNBOROUGH (ENGLAND) D M HOLFORD ET AL. MAR 84 1/1

UNCLASSIFIED RAE-TR-84031 DRIC-BR-93043 F/G 9/2 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

TR 84031

AD-A149 445

TR 84031

(9)

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 84031

March 1984

OPERATIONAL LOADS MEASUREMENT: A PHILOSOPHY AND ITS IMPLEMENTATION

by

Dorothy M. Holford
J. R. Sturgeon

Procurement Executive, Ministry of Defence
Farnborough Hants

UDC 629.13.052.6

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 84031

Received for printing 26 March 1984

OPERATIONAL LOADS MEASUREMENT: A PHILOSOPHY AND ITS IMPLEMENTATION

by

Dorothy M. Holford

J. R. Sturgeon

SUMMARY

A philosophy of operational data acquisition, for structural objectives, within the general field of in-flight load measurement is reviewed, highlighting the constraints such activities place on the data acquisition system. This Report describes one such system which can be tailored to perform a variety of tasks ranging from the collection of time histories of flight parameters or strain gauges to complex fatigue load analyses throughout the airframe. The system comprises a digital cassette recorder and a data acquisition unit within which a microprocessor is used for control of data acquisition and in-flight data analysis. System requirements in terms of accuracy, bandwidth and sampling rates are discussed for a range of aircraft types and operating conditions.

The various modes of operation of the system are illustrated by examples drawn from operational experience with the system. These demonstrate the capability of the system to produce data suitable for automatic analysis in a variety of operational environments in both fixed and rotary wing aircraft. The examples clearly show the value of studying operational data in terms of fatigue life management, fatigue life monitoring, operational practices and design procedures.

Departmental Reference: Materials/Structures 76

1

LIST OF CONTENTS

1 INTRODUCTION

Structural repair and maintenance costs can be several times the original cost of aircraft production. There is therefore, potentially, a rich reward for effective structural management within a fleet. The UK has directed its operational flight data acquisition and associated research programmes towards reducing unscheduled repair costs through a validation of the fatigue substantiation process, through understanding the causes of high fatigue damage rates and through the development of effective monitoring of structural usage fleetwide. Knowledge of the causes of high fatigue damage rates permits identification of load alleviation strategies which have no operational penalty. It is considered that realization of the first two aims can be accomplished by a comprehensive instrumentation fit to a relatively small number of aircraft covering the roles and theatres of the fleet. The aircrew operating procedures for the sample aircraft must be identical to other aircraft in the fleet so that they are not singled out for especial treatment. The investigative nature of the tasks demands that any airborne processing of the data shall not compromise the structural usage of the data, or eliminate the capability to diagnose faulty data.

Most UK military aircraft carry a fatigue load meter - a counting accelerometer with special levels and thresholds - the output of which can be used to monitor the fatigue life consumption of those components of the aircraft whose loading has a high correlation with normal acceleration in all fatigue damaging situations. To interpret the exceedance counts, assumptions must be made about the load distribution over the aircraft at the time the counts were registered. It can be seen that, for the modern combat aircraft with automatic stability and control systems, manoeuvre devices and other configuration control, use of the fatigue meter leaves many components unmonitored and gives rise to considerable uncertainties in the calculated fatigue consumption in others. Data from the operational load measurement programme can be used to improve the efficacy of current monitoring techniques and, if necessary, determine suitable alternatives.

In the course of the programme outlined above, methodology, airborne recording equipment, ground replay and analysis procedures have been developed and tailored to meet the exacting demands of the programme. It has been a process of evolution with successive programmes growing in complexity and benefiting from experience gained from preceding ones. All operational load measurement programmes are financed and monitored technically by MOD, the analysis of the data being carried out by the appropriate division of the aircraft contractor. This Report describes the overall philosophy of the load measurement programmes, the development of the recording system used in the majority of the programmes and illustrates its diverse capabilities with examples drawn from operational experience with the equipment.

Although this Report concentrates on the fatigue load measurement and monitoring aspects of data analysis, it is pertinent to note that the data are also examined to assess the adequacy of aircraft design requirements. The operational load measurement programme can also yield information of use in the design process. The nature of the

data analysis required in this context is the subject of further research programmes since the perceived nature of the structural loading and, to a certain extent, the aircraft response parameters are a function of the collecting aircraft's characteristics. These characteristics must be eliminated from the data in order for them to be relevant to a future aircraft.

2 DATA COLLECTION PHILOSOPHY

2.1 Operational load measurement programmes

These programmes seek to quantify the in-service fatigue life consumption and to determine the cause of high fatigue damage rates. The validation of the fatigue substantiation process invariably involves deduction of stress histories at particular structural features during service operation which can be assessed against those used in the determination of the fatigue performance of those features, eg as measured on the major fatigue test. The operational programme must collect loading data in a form which is most directly usable. Each component or major load path addressed by the programme must be considered from this standpoint. Essentially the question being asked is - what loading information is required given the fatigue substantiation process used? It is vital to pose this question in the planning stage because the analysis task must be defined and its implementation to hand when the operational data arrives. Critical analysis must proceed as the data are acquired to detect faults and false assumptions quickly. Otherwise the data will be consigned to storage and never be used. The fatigue analyst usually requires structural data in the form of local stresses or overall applied loads - torque, bending moment and shear - at particular stations. The operational load measurement programme must provide these data.

In the UK, consideration was given to evaluating structural loads from flight control and response parameters together with aircraft configuration and flight condition data. There are two distinct ways of dealing with the parametric data and it is important to be aware of the limitations inherent in each when used to calculate structural loads for fatigue purposes. In the first it is necessary to make assumptions about the underlying aerodynamic and inertial load distributions giving rise to the parametric data obtained. This must be done throughout the whole flight envelope for the many operating and environmental conditions met in practice. These load distributions are frequently not validated for each aircraft component. At frequencies appropriate to the aircraft's rigid body modes the totality of aircraft loading derivatives will have been used in handling investigations and in studies of flight control law performance etc. It is quite possible that the set of derivatives will have been tweaked to reproduce certain aircraft characteristics. However, such models frequently utilize parameters which are difficult to measure accurately. Additionally asymmetric flow breakdown, turbulence, aerodynamic interference effects and structural vibration all influence the required load distribution and are not necessarily reflected accurately in the whole aircraft model. Identification of these conditions and their effects on the desired load time histories further compound the interpretation of the parametric data in respect of applied load

distributions. Once the load distribution has been found, overall loads can be calculated or local stresses found from a structural model (eg a finite element model) - a process not without difficulty!

Alternatively, use may be made of load prediction equations[1] which are derived from a data base of loads and parameters by regression techniques[2]. These load prediction equations often reflect the statistical properties of the data base and may or may not represent the underlying physics of load generation. Their use outside the domain of the data base is therefore not advisable. Consequently the data base used to derive the parametric equations must be carefully selected, having regard to the number of specific manoeuvres/flight conditions occurring in service and their contribution to fatigue damage. This is unknown at the outset of the operational load measurement programme. Non-linearities and strong dependence on flight condition and vehicle configuration complicate and increase the number of load prediction equations required.

There are clearly many difficulties and uncertainties in evaluating structural loads from parametric data. Since the objective of the operational load measurement programme is to quantify the operational fatigue loading, the UK has favoured direct load measurement using strain gauge installations in those programmes. Structural load histories derived from strain gauge installations automatically include compensation for configuration changes and operational procedures whereas those derived from parameters do not. However, calculating loads from parameters means that the analyst can, in theory, compute loads anywhere in the structure whereas with direct load measurement he has to make a choice. His aim should be to quantify the loading conditions in the main load paths to give overall confidence in the fatigue substantiation procedures and in any known local fatigue sensitive areas. The gauge installation itself has to be carefully engineered to survive in the operational environment and produce usable data over long periods of time. Erratic performance of potentiometers, plugs and sockets, variability in insulation resistance, sensitivity to temperature and electrical and radio frequency interference must be eliminated, as far as possible, by careful design. All strain gauges are wired as complete four arm bridges at the measurement position. Where possible, strain gauge amplifiers should be sited close to the gauge installations so that long cable runs carrying low voltage signals are avoided.

The location and orientation of the strain gauge is critical since it gives a measurement of direct structural strain along its length in the immediate area of its location. In operational load measurement programmes gauges should be attached to well defined load carrying elements and in uniform and unidirectional stress fields away from stress concentrations. Each gauge installation should be chosen so that it predominantly responds to a desired single loading action unless the critical fatigue location is sensitive to more than one loading action. Local strain measurements can be used directly in fatigue calculations but, more usually, a 'fatigue calibration' is effected through a similar gauge installation on a major fatigue test specimen because it would never be wise to put an operational strain gauge at the local stress concentration which initiates the fatigue failure. Comparative spectra and rates of accumulation of fatigue damage can thus be established between the test specimen and the operational aircraft.

Sometimes it is necessary, because of the fatigue substantiation process used, to establish the proportions of component stresses at a critical feature or to estimate the overall applied torque, bending moment and shear distributions. In these circumstances a 'load calibration' is required. The latter is mainly used where it is necessary to relate the operational measurements to the input of a major fatigue test or, if sufficient detail can be provided in the overall load estimates, to permit fatigue calculations to be performed over the whole structure.

The structural loading data can be analysed for fatigue but to elucidate the causes of high fatigue damage rates the analyst must be able to establish associated aircraft motions and automatic system performance. Thus, in addition, flight parameters detailing flight condition, aircraft configuration, control demands and aircraft responses are also measured. Where appropriate the performance of stability augmentation systems and the like are also monitored. The parameter list is tailored to complement the structural fit and varies from aircraft programme to aircraft programme.

2.2 Fatigue monitoring

A fleetwide monitoring system should provide estimates of fatigue damage for critical structural components from the measured structural usage of the aircraft; give an indication as to whether a structural inspection is necessary; provide sufficient supplementary information to enable the operator to put a structural cost on his operations; and provide an assessment of the loading environment in major load paths and components for comparison with design assumptions.

For fleetwide implementation, the ground processing costs must be contained and disruption of operational turn-round procedures minimized. The results must be examined quickly in order to check serviceability of the monitoring system and identify damaging sorties. The cost and ease with which monitoring information can be used will dominate the issue of acceptance and usefulness of the system to the operator. This means that in the monitoring system the majority of the data processing must be done in real time during the mission. The fatigue meter is an excellent example of this philosophy. Its successor must provide more detailed coverage of the airframe and improve the accuracy of fatigue estimates by collecting structurally relevant statistics of load histories appropriate to each component monitored.

The need for more comprehensive fatigue monitoring on modern combat aircraft[1] is illustrated by the calculated taileron loading during two stylized rolling manoeuvres shown in Fig 1a&b. The normal acceleration is comparable in both cases but there is a factor of 2½ between the associated taileron loads which represents a factor of 15 to 50 on fatigue damage. Fig 1c illustrates the effect of manoeuvre demand control systems where, in the case illustrated, a rudder kick gives rise to taileron loads but no normal acceleration increment.

In the context of a fleetwide fit, there is obvious attraction in computing structural load time histories from easily measurable flight parameters and each case must be examined on its merits. However it must be remembered that the load prediction equations may become invalid if, during service, the operational procedures are changed

(section 2.1). For the case illustrated in Fig 1, acceptable load estimates can be obtained from a linear combination of normal acceleration at the centre of gravity, roll rate, symmetric taileron angle and differential taileron angle for a given flight condition, aircraft configuration and low angle of attack[1]. However the physcial loading mechanism in this flight regime varies markedly with aircraft configuration and flight condition. At high subsonic Mach numbers, different parametric equations are required for clean and multiple stores configurations. Also each equation is applicable over a restricted range of flight conditions. A large number of load equations will be needed to cover all flight regimes. This will render the parametric approach untenable if the operational load measurement programme shows that substantial fatigue damage is sustained in many flight regimes. By way of contrast, early work by Anne Burns et al[3] suggested that quite simple equations could be used to predict fin loads over a wide range of flight conditions. However the data[3] used did not contain significant information at frequencies above 1 Hz because low pass filters were used to remove activity at structural frequencies. Section 6.2 indicates that this bandwidth limitation leads to gross underestimates of damage rates in some flight conditions.

In a fleetwide monitoring system only those statistics of the loading environment necessary for fatigue evaluation can be economically computed. Currently it is envisaged that complete loading cycles within a loading waveform will be identified by a range-mean-pairs (rainflow) technique[4,5], and subsequently used with the remaining peaks and troughs to estimate fatigue damage (or crack growth) using simple cumulative damage algorithms. If necessary, residual stress effects (or crack retardation) can be introduced on a flight-by-flight basis.

An analysis technique to meet the objectives of fatigue monitoring is described in Ref 6. It provides damage estimates at regular intervals during the flight based on interim estimates of the fatigue resistance of the structural components. To find the causes for high fatigue damage rates it is necessary to supplement these estimates with broad brush aircraft state/configuration parameters at the time of the damage estimates. Such parameters might include the range of altitude, airspeed, normal acceleration at cg, lateral acceleration at cg, flap, slat, airbrake, nozzle angle, sweep angle etc during the last time interval. These data give the operator the basic information for fatigue management of the fleet. The technique is illustrated in Fig 2 which shows the fatigue damage profile for the wing of a large flexible aircraft. (The data are taken from Ref 6.) High fatigue damage rates and the relevant operating conditions can be identified and their validity established, to a certain extent, from the supplementary parametric information.

Load time histories directly related to fatigue critical features may be processed in the air to give, for each monitored station, fatigue damage on a flight-by-flight basis and a fatigue damage accumulation profile within a flight to meet the immediate objectives of fatigue monitoring. However the results of the intermediate process of loading cycle identification, ie the range-mean occurrence matrix for the whole flight, must be retained for future reassessment in the light of increased knowledge of the fatigue resistance of the structure.

3 RAMIFICATIONS OF DATA ACQUISITION

Studies of the structural implications of operational practices demand very high data quality for the analysis to be meaningful - complete flights must be analysed automatically and any data losses must be uncorrelated with structural loading severity. In the past many recorders have functioned reliably during innocuous flight conditions and consistently failed to function satisfactorily during structurally or aerodynamically severe flight conditions[7]. In operational load measurement programmes described in section 2.1, the data must be recovered in time history format to permit detailed investigation of the causes of high fatigue loads. The performance of the data acquisition system can therefore be readily assessed.

Of equal importance is the performance of the sensors. For the operational load measurement programmes to succeed, sensors must survive in the operational environment. Many data collection programmes have collected flight response data from accelerometers, potentiometers etc. These experiences suggested that these sensors would function reliably in the operational environment. There was however a question mark over the durability and stability of strain gauge installations in the operational environment. The first UK programme of the type described in section 2.1 began collecting data in 1977. Thirteen strain gauge bridges were attached to the wing of a Victor tanker aircraft. Of these one gauge failed within the first three months but the rest remained serviceable throughout the programme which collected data for three years*. Gauge datums and amplifier sensitivities remained sensibly constant throughout the programme. This encouraging experience sugested that, with placement of spare gauges alongside those to be recorded, the data acquisition programmes could produce structural loading data from strain gauges in service. However unserviceable sensors must be detected quickly otherwise much useless data may be collected. This means that the data must be verified for quality as soon as possible after collection, preferably within a week.

In the Victor programme mentioned above data were recorded on a fourteen track analogue FM recorder. Thirteen of the fourteen tracks were given over to strain gauge data while the flight response data were sampled digitally and written to the fourteenth track. The analogue recorder was used in our first programme for expediency. Digital data acquisition systems are preferred since they offer greater flexibility with respect to the number of parameters sampled and are less susceptible to electrical interference. However the Victor programme did give an opportunity to study the effects of limited bandwidth and sampling rates on fatigue loading patterns. These and other studies (sections 6.2 and 6.3) suggest that only the lower order structural modes are likely to be fatigue damaging in their own right. The major loading cycles emanate from control surface motions and the atmospheric environment but their magnitude may be substantially enhanced by the superposition of vibration loads. This means that typically load histories must be sampled at 8 to 64 samples/s depending on the predominant structural resonant frequencies. This provides information on the fatigue implications of the vibration but may not enable its frequency and phase characteristics to be deduced.

---

* Later programmes have utilized a subset of the original gauges; the latest programme in 1983 was mounted after major servicing in which the wing was removed and five of the original gauges were used in a more comprehensive coverage of the airframe.

In order to mount an operational loads measurement programme on a small combat aircraft, the data acquisition system must be relatively compact. However with compactness comes comparatively short duration recording at the required sampling rates. Therefore timewise data compression techniques must be used to reduce the quantity of data collected during structurally innocuous flight. This requires 'intelligence' on the part of the data acquisition system which can be supplied through a microprocessor based system. It is worth remembering that ground validation of the data and fatigue analysis are time-consuming and expensive and are proportional to the number of data words collected. Therefore the use of data compression techniques prior to data recording leads to a cost effective usage of ground analysis resources.

As discussed in section 2.1, for the fleetwide fatigue monitoring system the bulk of the fatigue analysis must be accomplished in the air. If, as is likely, the fatigue consumption of the modern combat aircraft can only be effectively monitored through access to a subset of the parameter list of the operational load measurement programme then it is clearly logical to think in terms of common equipments.

Engine Usage Monitoring Systems (EUMS) have been under development, under the direction of the Directorate of Engines MOD(PE) since the early 1970s[8]. The data acquisition and recording system was developed by Plessey and uses a Davall compact cassette tape recorder. The EUMS Mk I had an overall sampling rate of 32 samples/s and recorded data continuously on a single track of the cassette tape. There was no analysis capability. The EUMS Mk II was conceived as a microprocessor based system, with higher sampling rates and some airborne computational capacity. Materials and Structures Department, RAE have participated in the development programme with the aim of producing a versatile data acquisition and analysis system which would meet the diverse tasks of the operational loads measurement programmes.

Utilization of common data acquisition hardware for both structural and engine loads data measurement maximizes the return for equipment development costs. Scant research and support service resources are thus directed towards a definitive single entity with correspondingly greater return for that effort.

4 BASIC FEATURES OF THE EUMS MK II DATA ACQUISITION SYSTEM

The airborne data acquisition system that has evolved[9] is based on a digital flight recorder with microprocessor controlled data management. The microprocessor is used to control the acquisition of the data, its subsequent intermediate storage in a solid state memory and its final blocked transfer to compact cassette via a Davall 1207-003 tape recorder. The hardware development was carried out by Plessey under MOD contract. The main components of the airborne system are shown in Fig 3 in bench test arrangement. The system comprises the data acquisition unit, control unit and quick access tape recorder. The data acquisition unit accepts analogue signals from all standard transducers and converts them to 10 bit numbers at the desired sampling rates. Parameter sampling rates are controlled by software as is their position in the data frame format. The overall sampling rate is switchable and ranges from 8 to 512 words per second in binary steps.

Thus common digital recording hardware may be tailored by software changes to meet specific requirements. Signal conditioning boards can also be configured to suit particular applications[10].

The 10 data bits, an eleventh bit (used as a mode marker for timewise data compression, section 7) and a parity bit are assembled into a 12 bit word and stored in solid state intermediate memory silos. The data stream is assembled in an ARINC 573 code pattern[11]. Software controls whether or not a silo of data is subsequently transferred to cassette. The tape drive works in a stop/start mode and if data are to be output to tape, the tape is run up to its operating speed of 3 in/s when data are transferred from a silo of 2560 words at 1540 bits/in. When the silo is empty the tape drive stops. This recording mechanism results in a substantial increase in reliability since the tape transport mechanism is always recording data at a relatively high tape speed. Wow and flutter problems associated with low tape recording speeds are much reduced. Data quality is improved in the presence of severe structural vibration and the extreme event is certain to be actually recorded on the tape at least 1½ s after the event. By the use of parallel recording on four tracks of a compact cassette, over two million words are recorded on a single C-90 cassette. Data quality cassettes cost abo· ach and are thus an attractive data medium from an economic point of view. T ‚re cheap enough to be used once only and also provide an economic means of long ter ata storage. In the absence of data compression the recording durations for a C-90 cass ange from 20 h at 32 words/s to 1¼ h at 512 words/s. The compact cassette is quickly and easily transferred from its operational location to the ground analysis station. However there is also a family of ground support equipments which are used in the operational theatre to diagnose faults in the system and transducers. A flight line test set can be used to interrogate the digital data at selectable locations in the data format. Stability of ground datum values can be assessed for acceptability. A portable replay unit can produce hard copy data from the cassette if required.

5 OPERATIONAL EXPERIENCE WITH EUMS MK II

The pilot operational loads measurement programme on Victor clearly demonstrated the value of such programmes in removing speculation as to the origins and magnitudes of structural fatigue loading cycles. The first uses of EUMS Mk II in structural programmes on fixed wing aircraft were aimed at *ad hoc* problems and were restricted in their coverage of the airframe and the associated parameter fit. The programmes utilized equipments procured for engine usage studies, as in the case of Jaguar, or research purposes (Hercules and Sea King). The programmes are outlined in Table 1. The fitment of the system in a Sea King helicopter was by way of a pilot exercise to gather both flight usage data and engine torque data to establish the viability of the data acquisition system in the helicopter environment.

At RAE, data from each installation were studied in parallel. A number of sources of data corruption in the complete data acquisition/ground replay system were identified[12]. During these early programmes there was a continuing improvement in the quality of the data as successive error patterns were nullified. The installation on Jet

Provost in late 1981 incorporated most of the system improvements identified in the earlier programmes and discard rates of 1 in 10^4 to 10^5 words were achieved.

Residual errors were not associated with structural severity. It is likely that most were associated with power supply transients. Future installations will include a transient suppression unit which will hold up the power during a 50 ms break and also remove large spikes giving a stabilised power supply. These programmes have demonstrated that the system can produce data of high quality in the operational environment. However it must be recognized that no airborne digital recording system will ever produce flawless data. The analyst must ensure that error patterns in the data stream do not invalidate his analysis.

For the large transport aircraft, the sortie time is likely to exceed the cassette recording time. The simple EUMS Mk II becomes less attractive since crew action is required to change cassettes. However, with the Hercules programme, cassettes were changed at regular intervals enabling data to be collected throughout the sortie. It does mean that there are special instructions for operating the data collection aircraft of the fleet. This type of notoriety is usually avoided in an effort to ensure the data collected are representative of fleet usage. For future programmes, utilization of the EUMS Mk II with timewise data compression (section 7) may well obviate the need for crew action.

6 EXAMPLES TAKEN FROM THE OPERATIONAL LOAD MEASUREMENT PROGRAMMES USING EUMS MK II

6.1 General remarks

As mentioned in the Introduction, the operational loads data are analysed by the aircraft contractor to meet the direct objectives of the exercise. The examples presented here are taken from the investigative and research programmes at RAE. They illustrate that EUMS Mk II works well in diverse environments. The data have, in the main, been used to study the impact of sensor characteristics on analysis tasks. This work enables bandwidth and sampling rates for the more ambitious programmes (section 7) to be estimated with confidence.

The examples clearly show the need for accurate fatigue monitoring and illustrate the difficulties that are associated with deriving loads from aircraft response parameters. The strain gauge installations remained serviceable throughout the duration of the programmes (Table 1).

6.2 Empennage load measurement

6.2.1 Jaguar

The Jaguar programme showed that low-level operations were a major contribution to fatigue damage at the fin root. It was therefore most important that subsequent programmes should accurately assess the situation on other aircraft. Of the two aircraft in the Jaguar programme, one had a strain gauge amplifier bandwidth of 10 Hz and the other 40 Hz. The fundamental fin bending mode is about 12-13 Hz. Visual inspection of data from the 40 Hz bandwidth aircraft suggests that a few high frequency loading actions are

eliminated by the 10 Hz bandwidth amplifiers. The following discussion is based on data from the 10 Hz bandwidth system sampled at 32 samples/s. The life consumption analyses can be considered reasonably realistic for the real structure but are related to specific flight conditions. Any read across to total aircraft lives must include an assessment of how often the flight condition is met in practice.

Fig 4 shows a fatigue damage profile for a low-level sortie. The rate of fin fatigue damage varies within a patch of low-level flight, the damage rate quickly falling to zero (over a period of 5-15 s) when the aircraft gains altitude. The damage rate varied between flights - some flights had locally higher rates than those of Fig 4. These variations may well be associated with the terrain and/or the atmospheric environment. Strain data, typical of the period marked on Fig 4 are shown in the top trace of Fig 5 with an expanded time base to permit a more detailed study of its characteristics. The lower traces of Fig 5 show how these data are distorted as the bandwidth is reduced to 6, 1.8 and 0.9 Hz respectively by numerical filtering techniques. Dutch roll activity is a possible cause of the lower frequency component at about 0.8 Hz. The sharpness of the transient strain, perhaps due to a gust, at point A of the top trace of Fig 5 suggests that a higher bandwidth and sampling rate would be necessary to measure accurately its magnitude and characteristics.

As might be expected from a visual inspection of Fig 5, the bandwidth has a marked effect on computed life estimates and damage distributions. Damage rates per hour were estimated for the flight conditions of Fig 5 for each of the data bandwidths illustrated. A range-mean-pairs[4] analysis was used to produce the stress range exceedance count shown in Fig 6. It can be seen that relative to the raw data exceedance curve the 0.9 Hz bandwidth data reduces the stress range amplitude by a factor of 1.5 at the higher amplitudes and reduces the frequency of occurrence of the lower amplitude cycles by a factor of 3. The resulting damage distribution for the mean life S-N curve of Fig 6 is shown in Fig 7. The characteristic trend is for the maximum damage to be shifted to a lower stress amplitude and to be reduced in magnitude as the bandwidth of the data is reduced. The total damage is reduced by factors of 1.2, 2.8 and 12 for the 6 Hz, 1.8 Hz and 0.9 Hz bandwidths respectively.

6.2.2 Jet Provost

At entry into service the predicted fatigue life of the Jet Provost fin root was dominated by spinning. Unexpected fatigue failures led to an *ad hoc* operational load measurement programme. It was found that although the spins did produce severe structural activity, in fatigue damage terms, the type and extent of current low-level training proved more exacting. Based on Jaguar experience the strain gauge amplifiers of the Jet Provost programme had 40 Hz bandwidth, and fin and tailplane strain gauges were sampled at 32 samples/s.

Data from EUMS Mk II collected during stalls and spins are shown in Fig 8. It can be seen that the stalled wing condition leads to substantial high frequency structural activity at both the fin and the tailplane and some at the wing root. From the expanded time history of fin bending moment, Fig 9, it is evident that the raw data can only

indicate the severity of the high frequency loading components during the stall condition; higher sampling rates and/or bandwidth are necessary for accurate assessment and to detect individual erroneous data points. The raw data can however be used to identify such flight conditions/manoeuvres for which a more detailed assessment is necessary should their frequency of occurrence in the operational spectrum indicate a significant contribution to the total fatigue life consumption. It is pertinent to note, from the two lower traces of Fig 9, that this is still evident when the sampling rate is halved to 16 samples/s.

The section of low-level flight shown in Fig 10 is taken from a 38 minute period of low flying and represents average amplitudes of gauge outputs during that period. The dominant oscillation on the fin bending gauge is at about 0.6 Hz and is probably associated with Dutch roll activity. The bursts of activity which grow and decay may well be initiated by the pilot and/or the atmospheric environment. In this flight condition significant structural activity is for the most part confined to the fin in contrast to the spin data above. A portion of the fin gauge output was passed through the same set of numerical filters used in the Jaguar exercise. The result is shown in Fig 11. (The scales used are the same as those of Fig 9.) The 0.6 Hz stress reversals have superimposed on them varying amounts of high frequency activity which increase the fatigue damaging ranges. The increase is not uniform since the largest load cycle A of Fig 11 is virtually unaltered whereas others such as B and C are doubled when frequencies above 0.9 Hz are included.

6.2.3 General conclusions

Low-level operations have been a major contributor to fin fatigue problems on two aircraft: Jaguar and Jet Provost. In any assessment of fatigue damage throughout the operational spectrum it is important to use data of sufficient bandwidth and sampling rate so that fatigue damaging flight conditions/manoeuvres can be accurately identified and their damage contribution accurately quantified. It has been demonstrated, on Jaguar and Jet Provost operational flying, that empennage fatigue monitoring requires 10-40 Hz bandwidth and 32-64 samples/s. Only then can there be confidence in the calculated damage distribution and thus confidence in any read across to fleet lives.

6.3 Hercules

The prime objective of the Hercules programme was to measure wing loads during take off and landing. The only supportive flight parameter was normal acceleration. However data were collected throughout the flight. Some large sharp normal acceleration transients were seen on several flights during low-level support work. These were studied in some detail in view of the importance of low-level operations.

Current discrete gust requirements have evolved from normal acceleration data which were reduced to equivalent gust velocities under the assumption that the measured accelerations were due to the atmosphere. Normal acceleration data such as that of Ref 13 from the Civil Aircraft Airworthiness Data Recording Programme are frequently used in the

study of gust models and statistics. However the analyst must ensure that the bandwidth of the raw data is adequate for his analysis objectives. The following example from the Hercules programme shows how limited bandwidth can mask the true characteristic of the rarer large sharp transients. The data obtained from the EUMS Mk II are shown in Fig 12. The local meteorological conditions were reported as 3/8 cumulus at 1800 feet with a mean wind speed of 17 kn. The transient at A has the characteristic of a rotor; the wing strain gauges exhibit a similar pattern. The derived statistics of the normal acceleration transient are shown in Table 2. These remain substantially unaltered as the bandwidth is reduced down to about 3 Hz. At 0.9 Hz bandwidth the character of the original transient has been destroyed, the amplitude having been reduced by a factor of 1.3 and the width doubled. Reducing the sampling rate further degrades the perceived properties of the transient. It is important to note that these data were obtained at 210 kn TAS. Many civil and military gust encounters are likely to be at higher speeds so higher bandwidth and sampling rates become essential.

The data of Fig 13 are taken from a combat training sortie at low level. The manoeuvre of the last 25 s of Fig 13 was repeated some 1½ min later but without the transient loading at A. Of particular interest is the transient at B, almost certainly due to gust since it is out of character for a deliberate manoeuvre. The maximum rate of change of g is some 7.5 g/s, the g increment being 1.5 g achieved over a period of 0.375 s. Both this transient and the previous one are comparable, in magnitude and gradient distance, with the discrete gust of design requirements. Unless the conditions giving rise to such transients can be identified by the pilot, then the simultaneous occurrence of the manoeuvre and the transient must be a definite possibility resulting in a structural load substantially exceeding current design requirements. Research programmes to study the structural risk of low-level operations are underway as are programmes to collect atmospheric turbulence data at low level over a variety of terrains.

6.4 Sea King

The data of Fig 14 were obtained from a EUMS Mk II installation in a Sea King helicopter and show a rapid turn from rearwards flight relative to the air and ground which was reported by the pilot. These data illustrate how difficult it can be to identify some manoeuvres and modes of flying from parametric data. The control angles shown are pilot demands: these actions together with inputs from the automatic flight control system give rise to the measured responses. It is difficult, if not impossible to identify the rearwards flight from these data. Other conditions such as sideways flight can be equally difficult to identify. If such 'unidentifiable' manoeuvres contribute markedly to the fatigue life of a component it will be difficult to assess that component for fatigue unless a direct measurement of the required loading is obtained.

The turn of Fig 14 has an average rate of about 36 deg/s; the pilot has no instrument to indicate its severity and his physiological cues indicate a fairly benign environment. Normal acceleration at the rotor station and the tail are very close to 1 g suggesting that the pilot station likewise is at 1 g conditions. The lateral

acceleration at the cockpit is relatively innocuous but very large lateral accelerations and forces are generated at the tail particularly when stopping the turn.

Although the EUMS Mk II functioned competently in the helicopter environment the same cannot be said for one of the normal accelerometers at the rotor station which failed after about five flights. The trace, NCS, shown in Fig 14, is from the unserviceable instrument on the starboard side while NCP shows data from a serviceable instrument on the port side. The vibration at the NCS accelerometer location produced a number of short circuited turns of the accelerometer potentiometer near the 1 g position. This produces a fault easy to recognize visually but difficult to identify automatically.

The pilot exercise on Sea King, which collected data from 150 flights, showed that the data could be interrogated automatically and analysed even though all airborne/ground system enhancements currently in use were not implemented. Forthcoming programmes on Chinook and Sea King will employ EUMS Mk II equipment.

7 TIMEWISE DATA COMPRESSION

In order to extend the recording capacity of the basic EUMS Mk II, software and hardware have been developed to implement a timewise data compression algorithm which does not impair the structural usefulness of the data. Data acquisition systems with this capability are known generically as Structural Usage Monitoring System (SUMS) recorders[14]. The incoming data are always sampled at a pre-selected maximum overall word rate, eg 512 or 256 words/s, and stored in an internal buffer of capacity 3 × 1024 words. The latest 1024 words are examined, on acquisition, for structural severity by reference to six user nominated 'trigger' parameters. Structurally significant flight is presently identified if any one of the 'triggers' exceeds a preset, programmable, limit. In principle any logical expression which is a function of the six 'trigger' parameters can be used. If structurally significant activity is deemed present then the previous 1024 words of data will be output at maximum rate otherwise only 64 (or a binary multiple thereof, eg 128 or 256) user-selectable words of the 1024 will be output. This method ensures that the output data stream contains at least 2 s of pre-event data at high sampling rate and accurately tracks slowly changing datum conditions. Data are output at maximum rate until quiescent conditions have been maintained for a given, user-programmable interval of time.

SUMS recorders will be used in forthcoming operational load measurement programmes on Tornado, Buccaneer, Hawk and Jaguar aircraft. The SUMS recorder for Tornado[14] will operate at a maximum rate of 512 words/s and will initially be used with a compression ratio of 8:1. In compressed mode, the 64 words in a second will contain a reading for each parameter taken from within a narrow time slice. It is expected that the flight time recorded will be extended from 1¼ h to about 5 h. The first Tornado SUMS aircraft is expected to start collecting data in May/June 1984.

8 RANGE-MEAN-PAIRS ANALYSIS IN FLIGHT

During the fatigue analysis of the structural data from the operational loads measurement programmes, range-mean-pairs (rainflow) analyses are used to identify fatigue damaging loading cycles. The loading cycle is subsequently classified by its load range and mean load level and sorted into class cells whose boundaries reflect the requirement that each range-pair count in a cell can be assumed to produce a known amount of damage. The resolution used in the range-mean-pairs analysis must be sufficient to define accurately the boundaries of the matrix cells. The range-mean frequency of occurrence matrix is used in conjunction with a damage matrix to evaluate accrued damaged. Long-term storage of statistics of the loading environment, for future assessment, demands that only the structurally significant features of each load history be retained. The range-mean matrix provides the necessary basis (section 2.2). Clearly, producing the frequency of occurrence matrix in the air can reduce ground processing costs in the operational load measurement programmes if suitable load histories are defined *a priori*. Airborne analysis is a necessary prerequisite for the advanced fatigue monitor of section 2.2.

The microprocessor of the Hercules EUMS Mk II has been programmed to perform in-flight range-mean-pairs counting on all fifteen channels of data (14 strain gauges plus normal acceleration) in addition to its basic EUMS Mk II functions.

The occurrence matrices are accumulated in solid state memory and written to compact cassette at the end of the flight. The cassette therefore contains the raw data plus the results of in-flight analysis. Ground analysis has confirmed the correct functioning of the airborne computation.

The digitised loading data in a fatigue load monitoring system must encompass limit load conditions. At the same time the data must have sufficient resolution to cater for a variety of S-N curve shapes and low fatigue endurance limits (eg ± 1000 lb/in^2, ± 6.9 MN/m^2). To achieve this without introducing corrections for the grouping of the peak and trough values by the digitisation process, 256 resolution levels (8 bits) are needed. At 64 resolution levels substantial corrections for grouping will be required[5]. The EUMS Mk II has an 8 bit microprocessor and therefore the data were reduced from 10 bits to 8 bits prior to range-mean-pairs analysis.

A typical frequency of occurrence matrix recovered from the cassette tape is shown in Table 3. In this installation, the cell boundaries of the matrix were tailored to produce accurate estimates of damage due to low amplitude loading cycles postulating a low endurance structure. The cell sizes for the higher amplitude loading cycles are too large to allow exact calculation for any one flight because the counts per flight would be very low. However when many flights are summed, it is reasonable to assume that the counts, within a cell have a statistical distribution. The airborne algorithm[5,15] ensures that the largest amplitude cycle is separately identified as peak/trough values thus permitting a more detailed assessment of the effects of the once-per-flight loading cycle. Many more cells would contain counts during a severe flight.

9 CONCLUSIONS

The UK philosophy adopted in its operational load measurement programmes involves direct structural load measurement via strain gauge installations. These are supported by a flight parameter fit to identify the causes for high fatigue damage rates. Strain gauge installations have proved reliable in operational service.

The Engine Usage Monitoring System (EUMS Mk II), developed in the first instance for engine monitoring, has been used to collect the structural operational data on compact cassette. The system has been shown to work well in a number of different operational environments. The system is controlled by a microprocessor and can be tailored by software changes to meet specific requirements of a programme. The spare computing capacity of the microprocessor can be used for in-flight processing of the incoming data stream. In a particular application, range-mean-pairs analyses of fifteen data channels were performed and the results written to compact cassette at the end of the flight.

A derivate of EUMS Mk II known as Structural Usage Monitoring System (SUMS), has been developed to extend the flight time capacity of the compact cassette. In SUMS the microprocessor is used to effect a timewise data compression algorithm which does not impair the structural usefulness of the data. It is planned to use this data acquisition system for operational load measurement programmes on Tornado, Buccaneer, Hawk and Jaguar.

Data replay and analysis procedures have been developed to ensure that fault diagnosis and error correction can be controlled in the operational environment. The operational loads measurement programmes to date have, in virtually every instance, directed structural analysts to flight conditions/activities in which the structural penalties had not been fully appreciated. The programmes can provide a wealth of information on pilot operating techniques and the performance of automatic flight controls. This information can be used to produce design and operating recommendations that will conserve fatigue life with a negligible operational penalty. The programmes clearly demonstrate that different parts of the aircraft suffer fatigue damage in different operational activities and show that accurate fatigue life monitoring at many locations is essential to cost effective planning of fleet utilization.

Table 1

EXPERIENCE WITH EUMS MK II IN OPERATIONAL LOADS MEASUREMENT PROGRAMMES

Aircraft	No.	Programme dates	Word discard rate	Parameters
Sea King	1	September 1980 - April 1981	3 in 1000	Flight response and control data, rotor rev/min and engine torques.
Jaguar	2	June 1979 - May 1980 June 1980 - September 1981	Data unusable 1 in 100	Three channels strain data on empennage, height and speed.
Hercules	1	December 1980 - April 1983	3 in 1000 (start) 1 in 10000	Fourteen channels strain data on wing, normal acceleration.
Jet Provost	2	October 1981 - April 1982	1 in 10000 to 100000	Eight channels strain data on empennage (7), and wing (1), normal and lateral (tail) acceleration.
Sea King	1	November 1983 -		Flight response and control data, rotor rev/min, engine torque, tail rotor torque, one strain gauge channel on airframe (choice of three switchable).

Table 2

EFFECT OF BANDWIDTH AND SAMPLING RATE ON THE CHARACTERISTICS OF THE HERCULES TRANSIENT "A" OF FIG 12

Transient characteristic	Sampling rate 16 samples/s		Sampling rate 8 samples/s	
	Bandwidth of data		Bandwidth of data	
	15.5 Hz*	0.9 Hz	15.5 Hz	0.9 Hz
$\lvert g\ \text{peak} - g\ \text{trough}\rvert$ (g units)	1.69	1.23	1.62→1.69	1.21→1.23
$\lvert \text{time peak} - \text{time trough}\rvert$ (seconds)	0.344	0.719	0.375	0.75
$\left.\frac{\Delta g}{\Delta t}\right\rvert_{max}$ (g units/s)	7.84	2.72	6.8→7.68	2.56→2.64

*The raw data has bandwidth 15.5 Hz and were sampled at 16 samples/s.

Table 3

HERCULES: RANGE-MEAN-PAIRS COUNT OF A WING STRAIN GAUGE

Matrix for Channel 13

	Range in digits																					
	10–11	12–15	16–19	20–23	24–27	28–31	32–39	40–47	48–55	56–63	64–79	80–95	96–111	112–127	128–143	144–159	160–175	176–191	192–207	208–223	224–239	240–255
0– 31	0	0	0	0	0	0	0	0	0	0												
32– 63	0	0	0	0	0	0	0	0	0	0	0	0	0	0								
M 64– 95	17	22	9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
E 96–127	1	4	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
A 128–159	76	81	25	7	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N 160–191	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
192–223	0	0	0	0	0	0	0	0	0	0	0	0	0	0								
224–255	0	0	0	0	0	0	0	0	0	0												

Airborne manoeuvres and gusts

Possible rotation or bounce landing counts

Taxiway and runway counts

Ground-air-ground count

REFERENCES

No.	Author	Title, etc
1	Dorothy M. Holford	Generation of load equations from flight parameters for use in fatigue life monitoring. RAE Technical Report 81133 (1981).
2	N.R. Draper, H. Smith	Applied regression analysis. John Wiley and Sons Inc. Second Edition 1981.
3	Anne Burns, J.P. Thompson E.W. Wells	The development of a parametric method of measuring fin fatigue loads based on flight measurements on a Lightning Mk T5. ARC R&M 3824, December 1976.
4	Susan D. Ellis	A combined range-mean-pairs rainflow count of load time histories for use in the formulation of structurally relevant cost functions and fatigue analysis. RAE Technical Report 81122 (1981).
5	Dorothy M. Holford	Implementation of range-mean-pairs analysis on an operational aircraft for fatigue life estimation." RAE Technical Report in preparation.
6	Dorothy M. Holford	The role of a fatigue damage accumulation plot in structural loads data analysis. RAE Technical Report 82125 (1982).
7	J.R. Sturgeon	Operational data acquisition and analysis for monitoring of military aircraft usage. RAeS/IEE AIDS Symposium 5 April 1978.
8	M.F. Hurry, C.M. Connor	United Kingdom military engine usage, condition and maintenance systems experience. AIAA-83-1239 June 1983.
9	-	Target production specification for Engine Usage Monitoring System. Specification 612/SA/36580, The Plessey Co Ltd, Havant (1977)
10	-	Proposal for helicopter fatigue monitoring system, Type PV1820A. The Plessey Co. Ltd, Havant (1977)
11	Airlines Electronic Engineering Committee	ARINC characteristics No. 573-5, aircraft integrated data system (AIDS Mk 2). Aeronautical Radio Inc, May 1971.
12	B.T. Remnant	The retrieval and graphical presentation of aircraft response data recorded digitally on a compact cassette during squadron operations. RAE Technical Memorandum Structures 1013 (1982)

REFERENCES (concluded)

No.	Author	Title, etc
13	Susan D. Ellis	A presentation of measured aircraft responses in turbulence during civil operations. RAE Technical Report 78113 (1978).
14	-	Specification for a Structural Usage Monitoring System for Tornado aircraft, 4769/82/21. The Plessey Co Ltd, Havant (1982)
15	W.L. Walters	A method for the analysis of a fatigue history waveform for use with a microcomputer. RAE Technical Memorandum Structures 943 (1979)

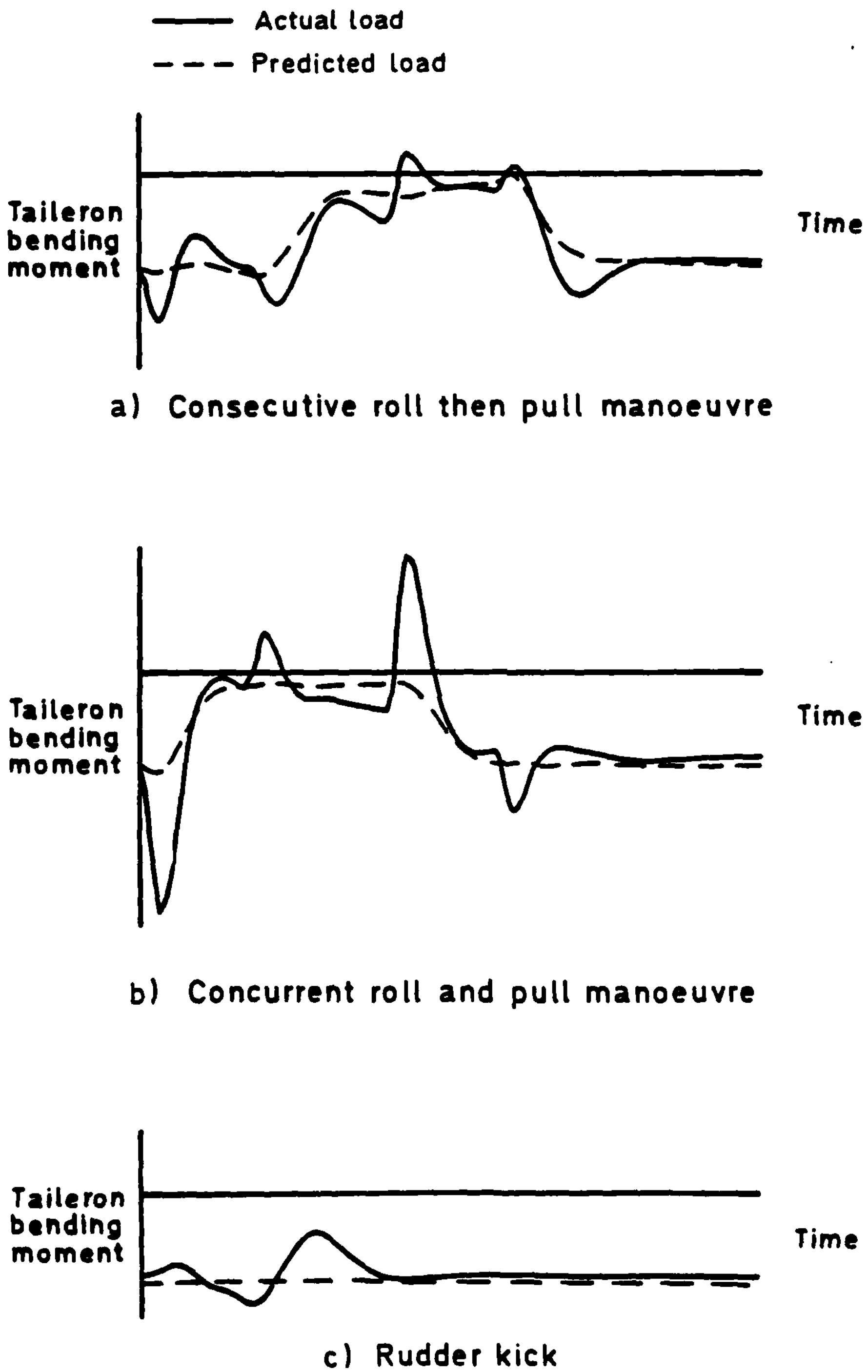


Fig 1a-c Comparison of actual load and that predicted from the normal acceleration at cg, n_z

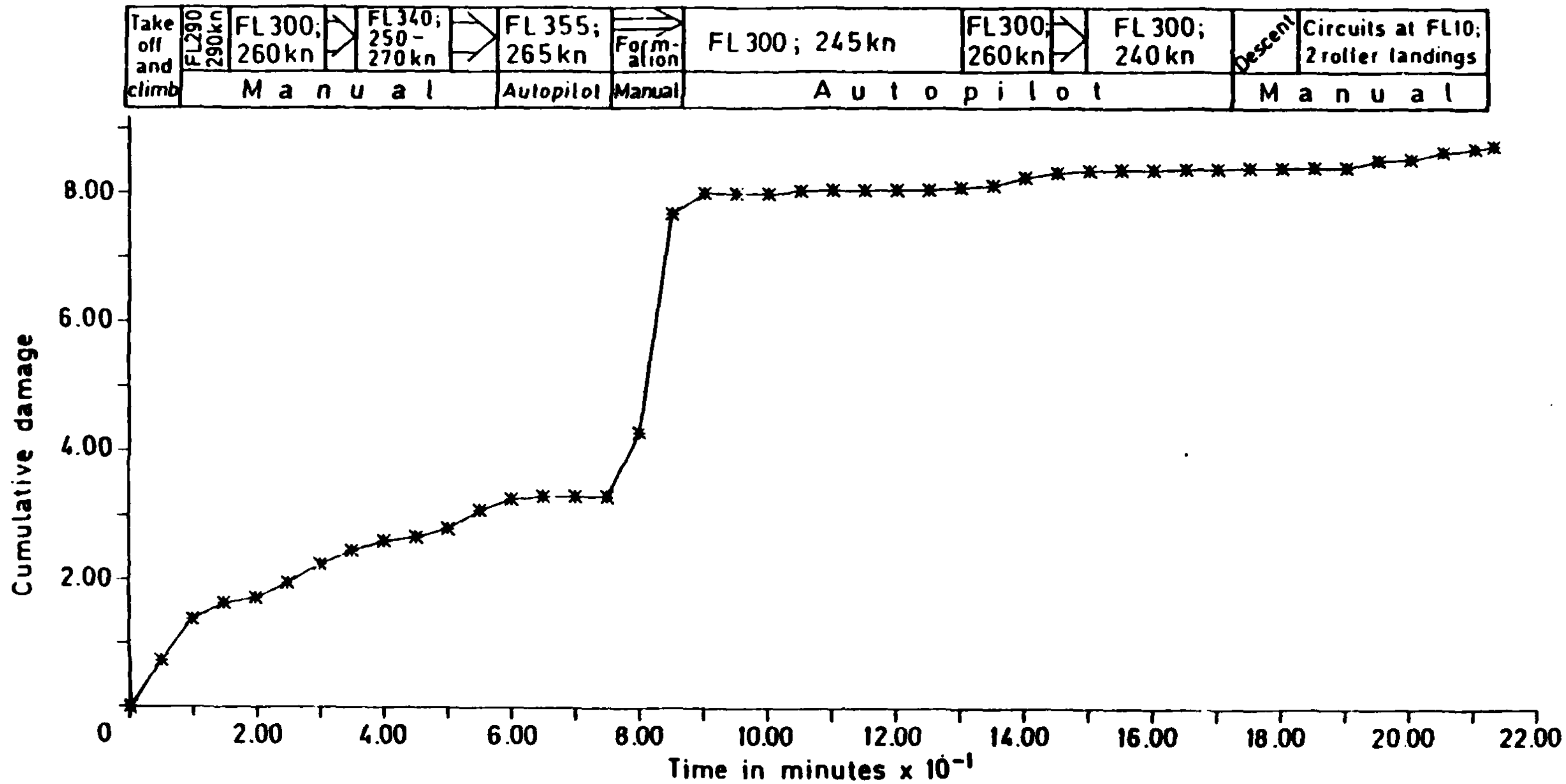


Fig 2 Damage accumulation profile and associated flight conditions for a wing feature of a large flexible aircraft

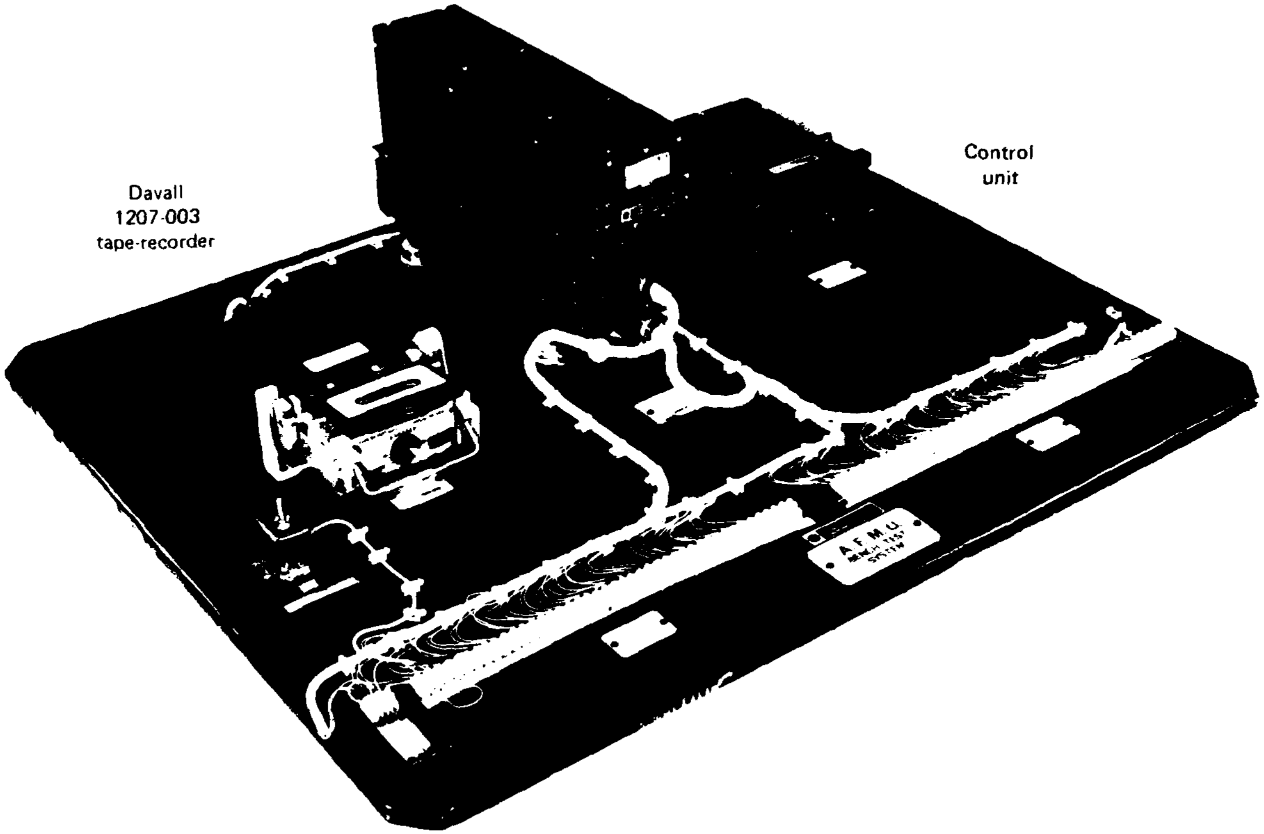


Fig 3 Operational load data acquisition system. bench test layout

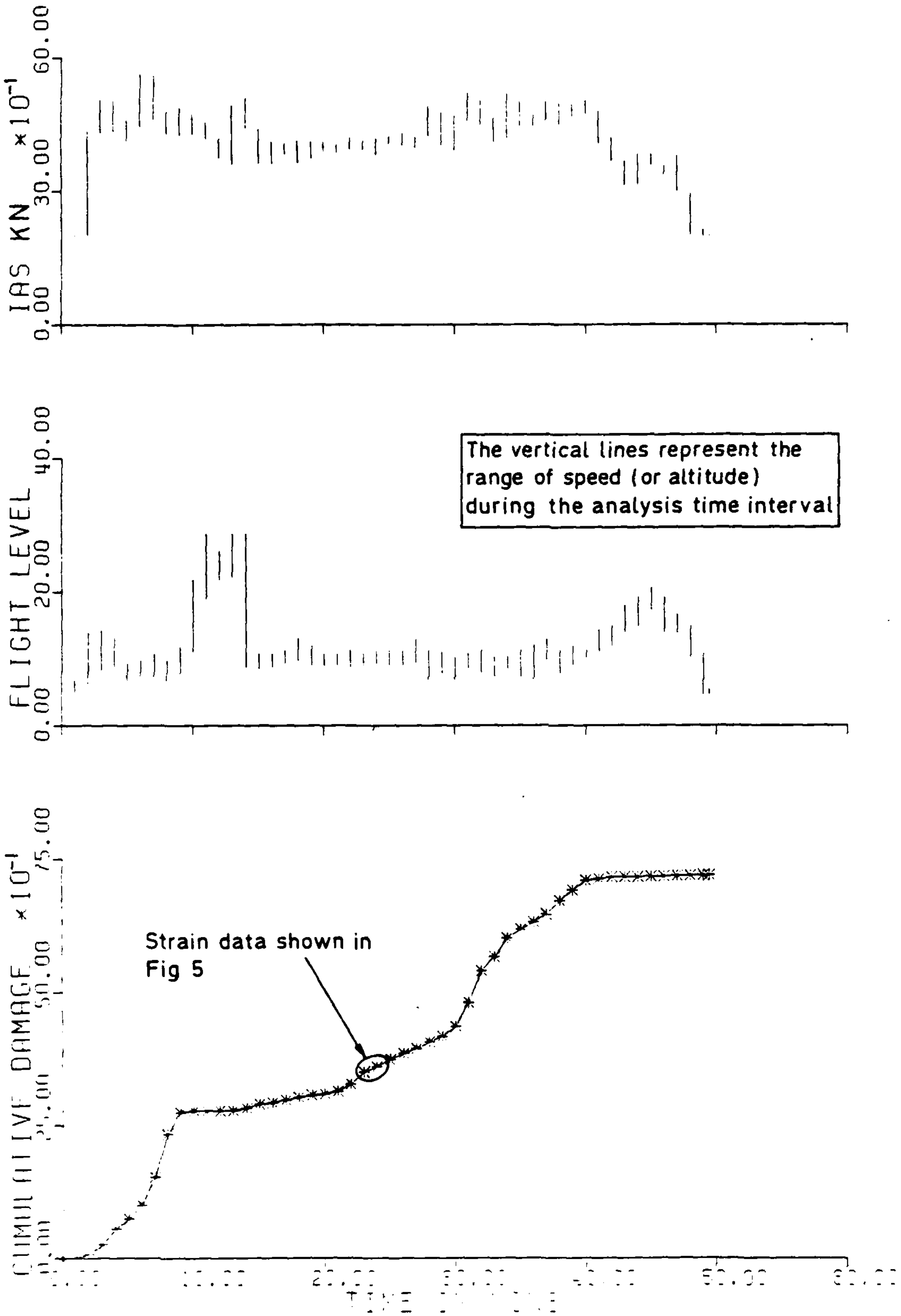


Fig 4 Damage profile and flight conditions for a low level sortie

TR 84031

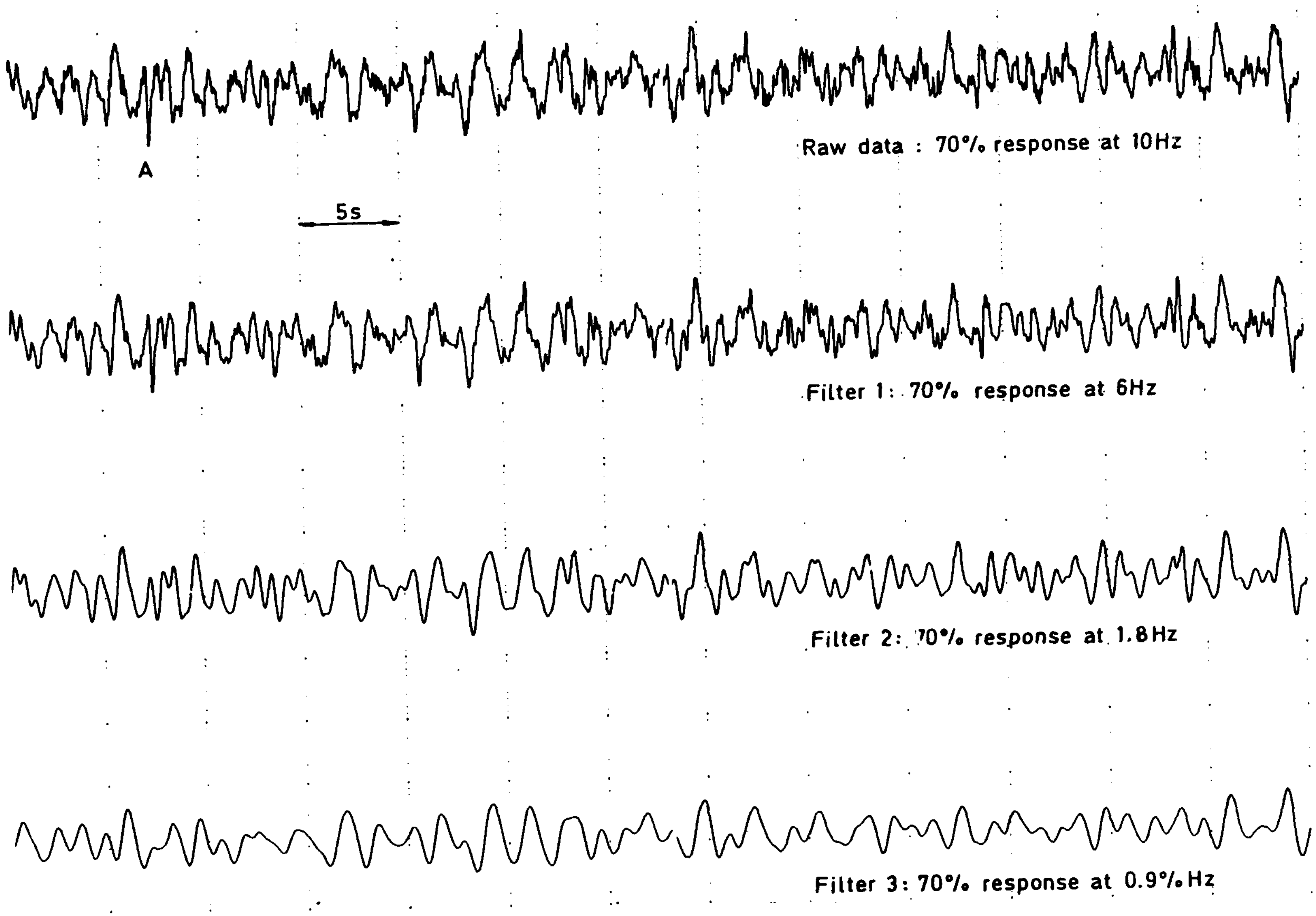


Fig 5 Effect of frequency bandwidth on Jaguar fin strain measurements during low level flight

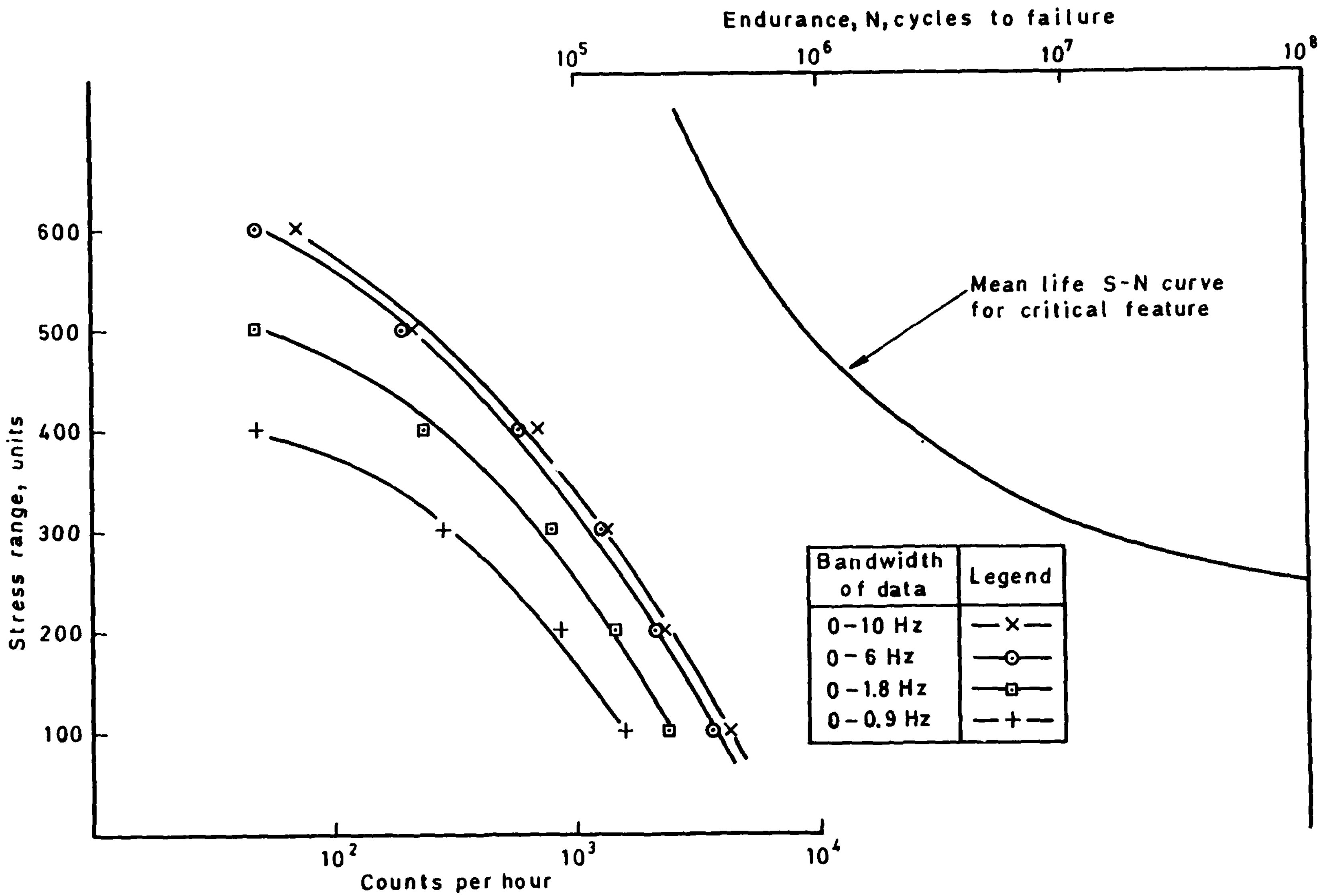


Fig 6 Effect of bandwidth on stress range exceedance count and S-N curve for a critical feature

The graphs join mid-cell points of the underlying damage histogram which is illustrated for +——+ curve only
The dashed lines indicate regions where the result might be unduly influenced by sample size

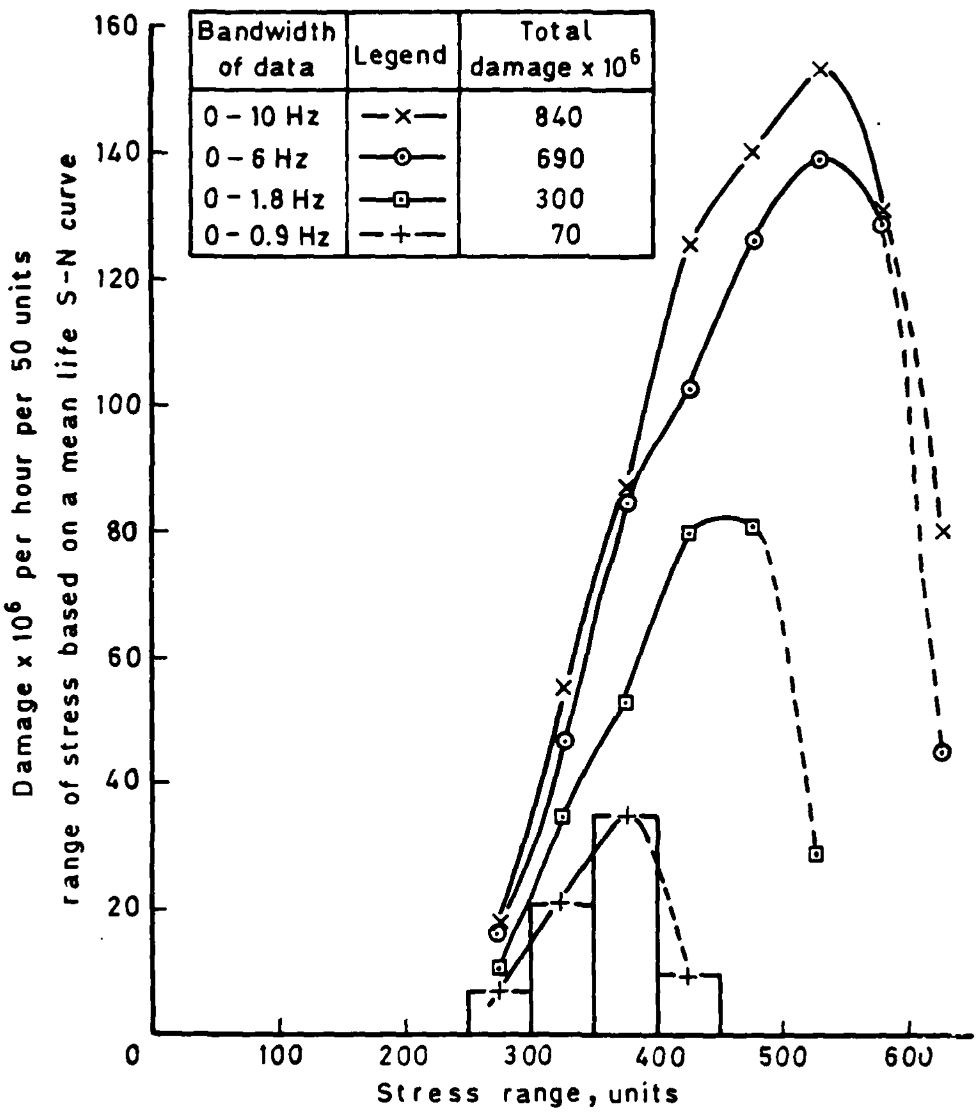


Fig 7 Effect of bandwidth on damage distribution for a particular feature

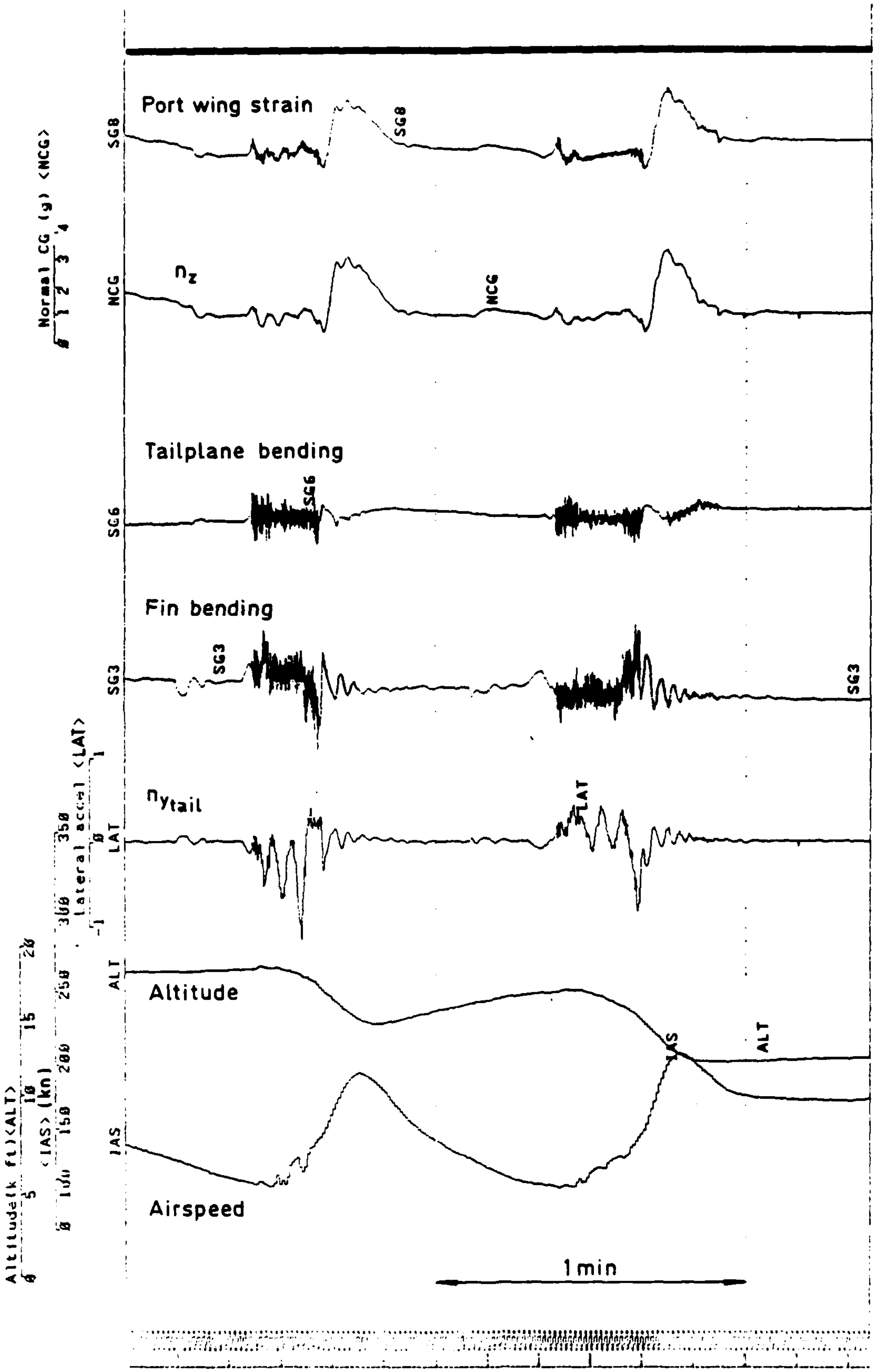


Fig 8 Jet Provost: structural activity during spins

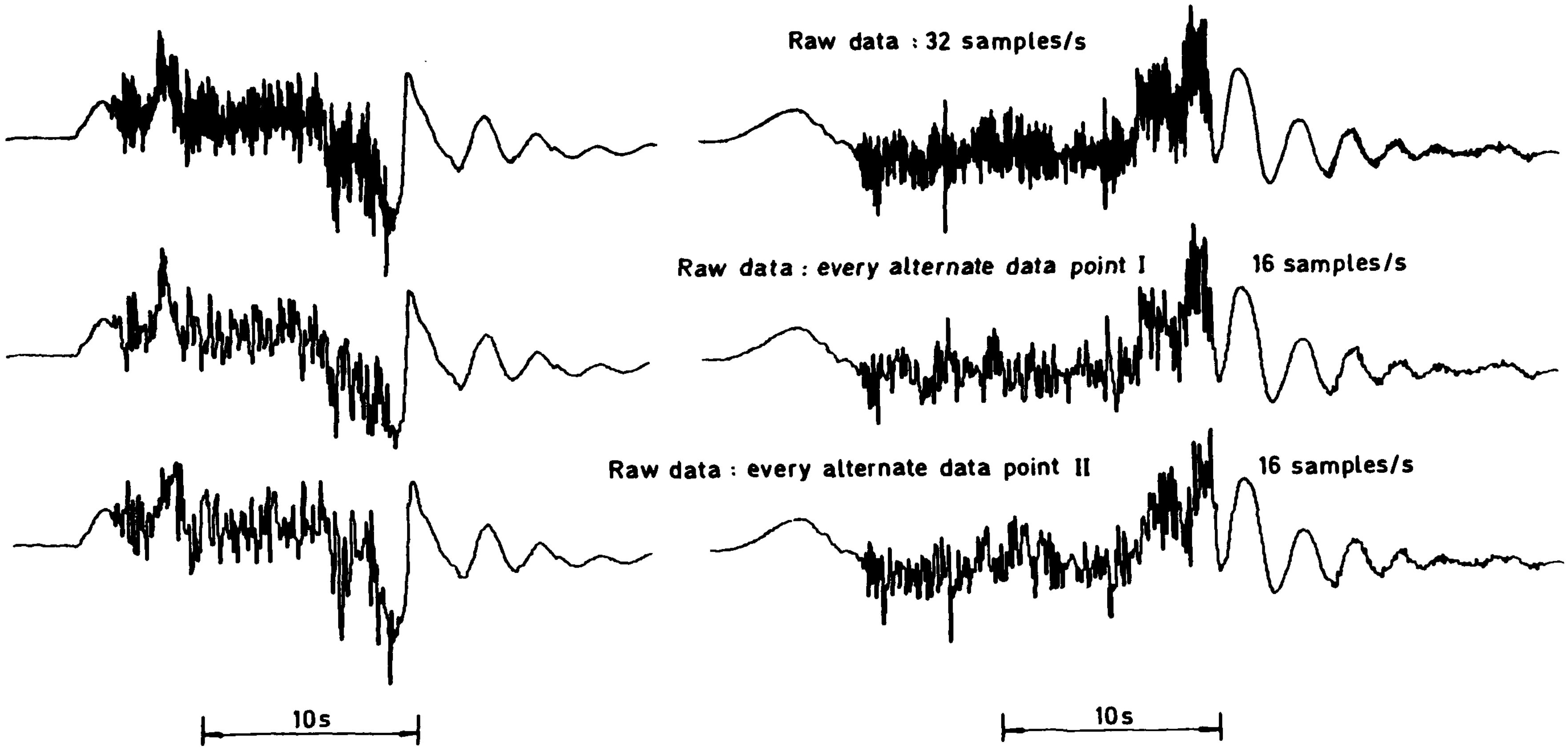


Fig 9 Jet Provost: fin bending moment during stalls and spins

Fig 10

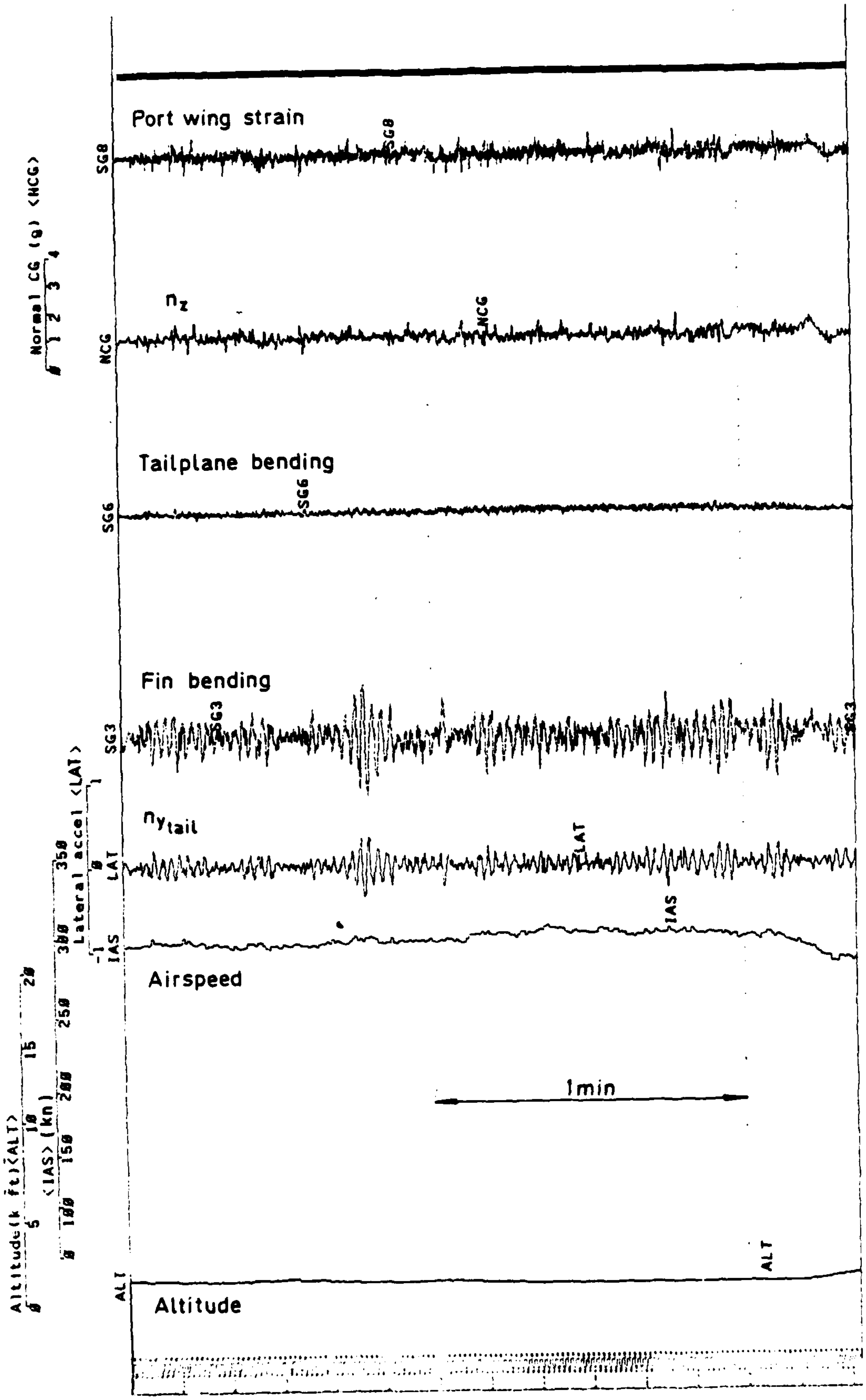


Fig 10 Jet Provost: typical record from a low level flight

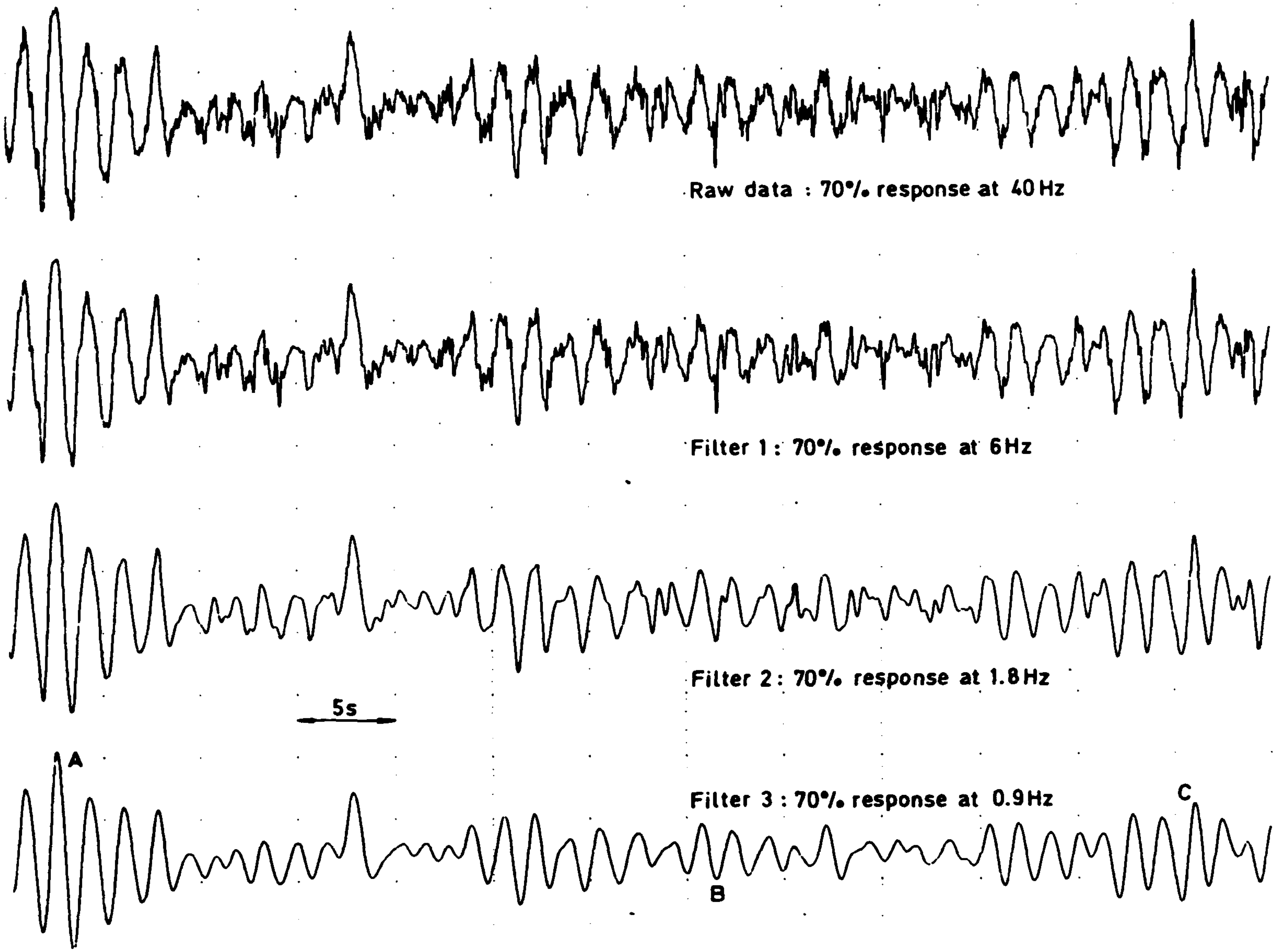


Fig 11 Jet Provost: effect of frequency bandwidth on output of a fin gauge during low level flight

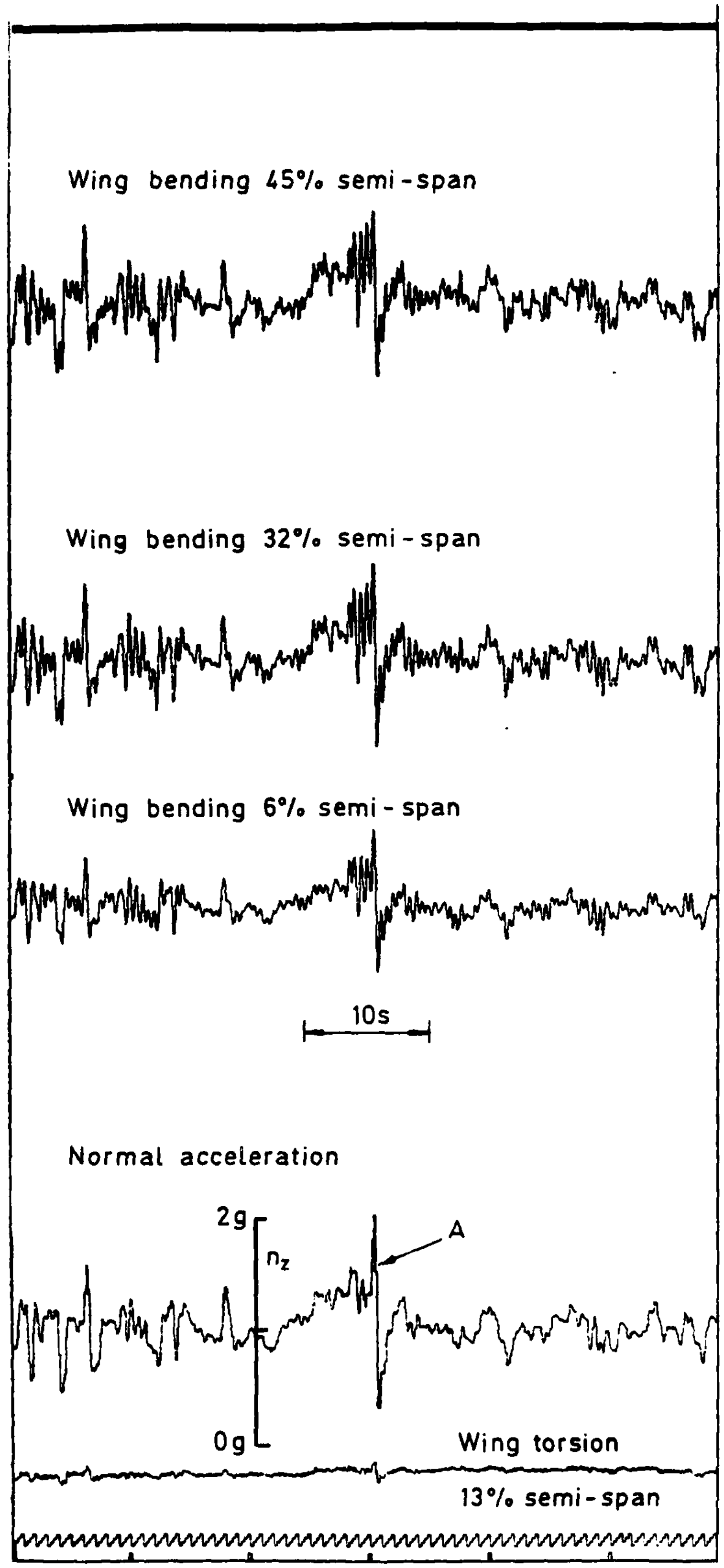


Fig 12 Strain gauge outputs and normal acceleration on Hercules: IAS ≏ 210 kn, altitude < 1500 ft, 3/8 cumulus at 1800 ft and mean wind 17 kn

TR 84031

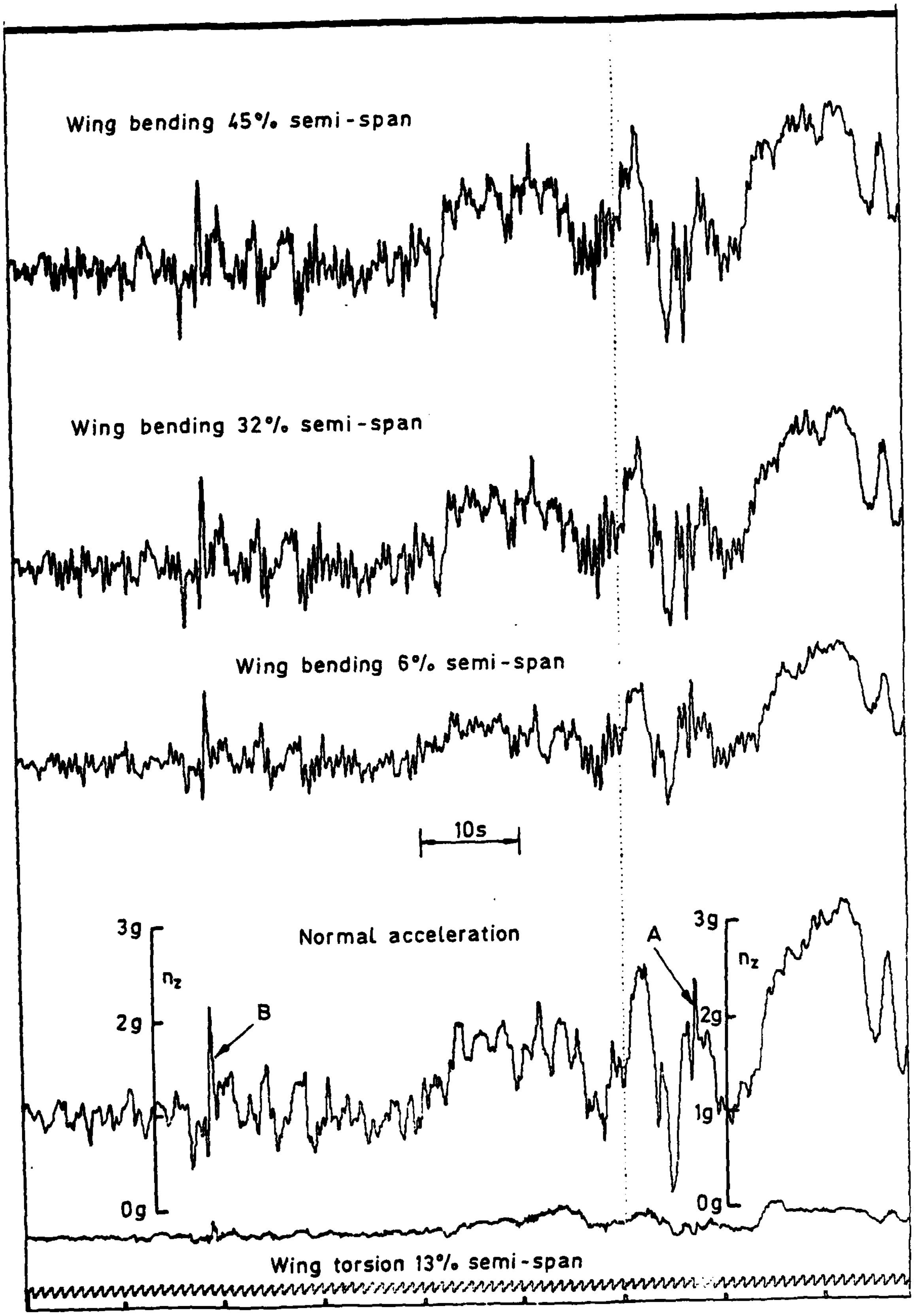


Fig 13 Strain gauge outputs and normal acceleration at cg measured on Hercules during a combat training exercise: IAS ≏ 210 kn, altitude < 1500 ft

Fig 14

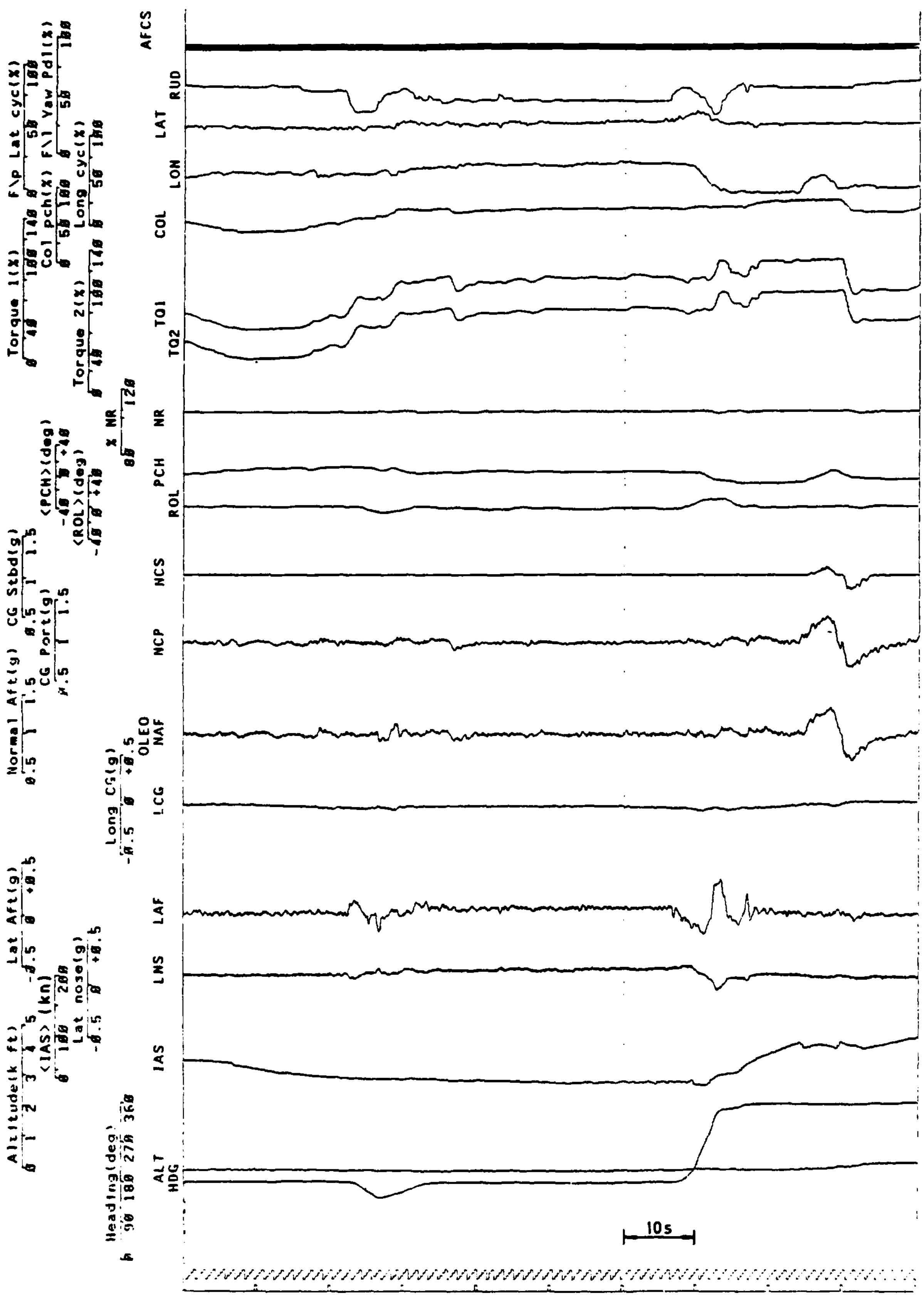


Fig 14 Sea King rapid turn from rearwards flight

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNLIMITED

s far as possible this page should contain only unclassified information. If it is necessary to enter classified information, the box ɔove must be marked to indicate the classification, e.g. Restricted, Confidential or Secret.

1. DRIC Reference (to be added by DRIC)	2. Originator's Reference	3. Agency Reference	4. Report Security Classification/Marking
	RAE TR 84031	N/A	UNLIMITED

5. DRIC Code for Originator	6. Originator (Corporate Author) Name and Location
7673000W	Royal Aircraft Establishment, Farnborough, Hants, UK
5a. Sponsoring Agency's Code	**6a. Sponsoring Agency (Contract Authority) Name and Location**
N/A	N/A

7. Title Operational loads measurement: a philosophy and its implementation.

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference
AGARD, SMP Specialists Meeting 'Operational Loads Data', Siena, Italy, 2-4 April 1984.

8. Author 1. Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	Pages	Refs.
Holford, Dorothy M.	Sturgeon, J.R.		March 1984	35	15

11. Contract Number	12. Period	13. Project	14. Other Reference Nos.
N/A	N/A		Materials/Structures 76

15. Distribution statement
(a) Controlled by –
(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)
Structural fatigue. Operational loads. Flight data acquisition. Fatigue monitoring.

17. Abstract

A philosophy of operational data acquisition, for structural objectives, within the general field of in-flight load measurement is reviewed, highlighting the constraints such activities place on the data acquisition system. This Report describes one such system which can be tailored to perform a variety of tasks ranging from the collection of time histories of flight parameters or strain gauges to complex fatigue load analyses throughout the airframe. The system comprises a digital cassette recorder and a data acquisition unit within which a microprocessor is used for control of data acquisition and in-flight data analysis. System requirements in terms of accuracy, bandwidth and sampling rates are discussed for a range of aircraft types and operating conditions.

The various modes of operation of the system are illustrated by examples drawn from operational experience with the system. These demonstrate the capability of the system to produce data suitable for automatic analysis in a variety of operational environments in both fixed and rotary wing aircraft. The examples clearly show the value of studying operational data in terms of fatigue life management, fatigue life monitoring, operational practices and design procedures.

END

FILMED

2-85

DTIC